Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L. Oskinova, eds.
Potsdam: Univ.-Verl., 2007
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

The impact of reduced mass loss rates on the evolution of massive stars

Raphael HIRSCHI
University of Keele, United Kingdom

Mass loss is a very important aspect of the life of massive stars. After briefly reviewing its importance, we discuss the impact of the recently proposed downward revision of mass loss rates due to clumping (difficulty to form Wolf-Rayet stars and production of critically rotating stars). Although a small reduction might be allowed, large reduction factors around ten are disfavoured.

We then discuss the possibility of significant mass loss at very low metallicity due to stars reaching break-up velocities and especially due to the metal enrichment of the surface of the star via rotational and convective mixing. This significant mass loss may help the first very massive stars avoid the fate of pair-creation supernova, the chemical signature of which is not observed in extremely metal poor stars. The chemical composition of the very low metallicity winds is very similar to that of the most metal poor star known to date, HE1327-2326 and offer an interesting explanation for the origin of the metals in this star.

We also discuss the importance of mass loss in the context of long and soft gamma-ray bursts and pair-creation supernovae. Finally, we would like to stress that mass loss in cooler parts of the HR-diagram (luminous blue variable and yellow and red supergiant stages) are much more uncertain than in the hot part. More work needs to be done in these areas to better constrain the evolution of the most massive stars.

1 Introduction

Mass loss has a crucial impact on the evolution of massive stars. It affects evolutionary tracks, lifetimes and surface abundances. It also determines the population of massive stars (number of stars in each Wolf-Rayet subtype for example). It influences the type of supernova at the death of the star (SNII, Ib, Ic, or a pair-creation supernova) and the final remnant (neutron star or black hole). Mass loss releases matter and energy back into the interstellar medium in amounts comparable to supernovae (for stars above 30 $M_\odot$). Finally, it affects the hardness of the ionizing radiation coming from massive stars. It is therefore very important to understand mass loss in order to understand and model the evolution of massive stars.

2 Impact of reduced mass loss rates at solar metallicity

The concept of clumping is not new (see contribution from Moffat in this volume, or a general review from Kudritzki & Puls 2000). However, new observations suggest clumping factors leading to downward revision of mass loss rates between three to ten or even more for massive stars (Bouret et al. 2005, Fullerton et al. 2006). Here we discuss the implications of a reduction factor around ten. A 120 $M_\odot$ star, using current mass loss prescriptions at solar metallicity (Vink et al. 2000, 2001, Kudritzki & Puls 2000), loses on average $2 \cdot 10^{-5}\, M_\odot$ per year. The lifetime of a 120 $M_\odot$ star is about 2.5 million years. This implies that, on the main sequence, a 120 $M_\odot$ star loses approximately 50 $M_\odot$. If mass loss rates are reduced by a factor 10, such a star would only lose 5 $M_\odot$. The question is then, how to produce a WR star with such low mass loss rates? The first possibility is that mass loss is high in other evolutionary stages, like the luminous blue variable (continuum-driven winds in LBVs, Smith & Owocki 2006) and the red supergiant (RSG) stages. Mass loss rates are harder to determine in these two stages and therefore uncertainties are still large. Nevertheless clumping may also affect mass loss determination in other stages. Another possibility would be that all massive stars are in close binary systems (Kobulnicky et al. 2006). However, if this were true, then it would be hard to produce the many RSG stars observed. Furthermore, the fraction of Wolf-Rayet stars in close binary systems in the Magellanic Clouds is found to be only 30-40% (Foellmi et al. 2003, 2003). This means that single stars must still be able to lose enough mass to become WRs on their own. The last possibility discussed here is that rotation (possibly coupled to magnetic fields) induces such a strong mixing that WRs are produced by mixing rather than mass loss (Maeder 1987, Yoon & Langer 2005). This scenario works only for fast rotators, which represent only a

small fraction at $Z_\odot$ and therefore this cannot produce all the WR stars observed.

Another important impact of strongly reduced mass loss rates is that it implies that the angular momentum loss is much weaker. This would lead to many critically rotating stars near the end of the main sequence, similar to Be stars. This in turn would lead to an increase in mass loss rates, which could possibly compensate for a modest reduction factor. Additional models are necessary to give a quantitative answer. More interestingly, mass loss would become strongly anisotropic (Maeder & Desjacques 2001) and possibly produce disks when the Ω-limit is reached as is observed around Be type stars (See e.g. the review by Porter & Rivinius 2003). The lack of observations of critically rotating very massive stars is an argument against mass loss being extremely low on the main sequence and high only later on during the LBV and RSG stages. Note that rotation is able to compensate for a reduction factor 2 for mass loss since comparable number of WR stars are produced with enhanced mass loss rates (Meynet et al. 1994) and with normal mass loss rates + rotation (Meynet & Maeder 2005).

3 Metallicity dependence

The metallicity (Z) dependence of mass loss rates is usually included using the formula: $\dot{M}(Z) = \dot{M}(Z_\odot)(Z/Z_\odot)^\alpha$. The exponent α varies between 0.5-0.6 (Kudritzki & Puls 2000, Kudritzki 2002) and 0.7-0.86 (Vink and collaborators 2001, 2005) for O-type and WR stars (See Mokiem et al. 2007 for a recent comparison between mass loss prescriptions and observed mass loss rates). Until very recently, most models use at best the total metal content present at the surface of the star to determine the mass loss rate. However, the surface chemical composition becomes very different from the solar mixture, due either to mass loss in the WR stage or by internal mixing (convection and rotation) after the main sequence. It is therefore important to know the contribution from each chemical species to opacity and mass loss. Recent studies (Vink et al. 2000, 2005) show that iron is the dominant element concerning radiation line-driven mass loss for O-type and WR stars. In the case of WR stars, there is however a plateau at low metallicity due to the contributions from light elements like carbon, nitrogen and oxygen (CNO). In the RSG stage, rates generally used are still those of Nieuwenhuijzen & de Jager (1990). Observations indicate that there is a very weak dependence of dust-driven mass loss on metallicity and that CNO elements and especially nucleation seed components like silicon and titanium are dominant (Van Loon 2000, 2006, Ferrarotti & Gail 2006). See van Loon et al. (2005) for recent mass loss rate prescriptions in the RSG stage. In particular, the ratio of carbon to oxygen is important to determine which kind of molecules and dusts form. If the ratio of carbon to oxygen is larger than one, then carbon-rich dust would form, and more likely drive a wind since they are more opaque than oxygen-rich dust at low metallicity (Höfner & Andersen 2007).

In between the hot and cool parts of the HR-diagram, mass loss is not well understood. Observations of the LBV stage indicate that several solar masses per year may be lost and there is no indication of a metallicity dependence. Chromospheric activity could also play a role in stars having surface temperature similar to the Sun. Thermally driven winds and pulsations are still other ways to lose mass. Even though there are still large uncertainties in the dependence of the mass loss rates on metallicity in the cooler part of the HR-diagram, it is very useful to use models and observations at various metallicities. Indeed, clumping appears to be metallicity independent and therefore comparisons between models and observations should yield the same conclusions at different metallicities. Furthermore, using models at lower metallicity already give a very good estimate of what the impact of clumping may be on the evolution of the star. The mass loss rate is a factor 1.6-2.2 (depending on alpha) and 2.2-4.0 lower at the metallicity of the large and small Magellanic Clouds (LMC and SMC) respectively. Comparing models calculated at the SMC metallicity with observations at solar metallicity shows the impact of a reduction factor around three.

Several groups recently computed massive star models and compared them to observed populations around solar metallicities. Here we present a few of them. Meynet & Maeder (2005) compare the ratio or WR to O-type stars using α=0.5 for O-type star and no metallicity dependence for WR stars. They find that rotating models better reproduce the WR/O ratio and also the ratio of type Ib+Ic to type II supernova as a function of metallicity compared to non-rotating models, which underestimate these ratios. Reducing the mass loss rates by even a factor two would not fit the observations as well as with the current mass loss prescriptions. Eldridge & Vink (2006) use mass loss rates dependent on metallicity in the WR stage and find a better agreement with observations for the WC/WN ratio compared to metallicity independent mass loss rates in the WR stage. Again, reducing the mass loss rates by a factor 2 or more would not fit the data better than with the current mass loss prescriptions. However Vanbeveren et al. (2007) includes binary stars in the comparison and find a good fit with a mass loss rate reduced by a factor two.

Including all the arguments discussed above, from the current stellar evolution point of view the observations of the populations of massive stars would not be better reproduced with mass loss rate prescriptions reduced by a factor greater than two.

4 First stellar generations

As we saw in the previous sections, mass loss plays a crucial in the evolution of solar metallicity stars. In this section, we discuss the importance of mass loss on the evolution of the first stellar generations. The first massive stars died a long time ago and will probably never be detected directly (see however Scannapieco et al. 2005). There are nevertheless indirect observational constraints on the first stars coming from observations of the most metal poor halo stars (Beers & Christlieb 2005). The first stars are very important because they took part in the re-ionisation of the universe at the end of the dark ages (roughly 400 million years after the Big Bang). They are therefore tightly linked to the formation of the first structures in the universe and can provide valuable information about the early evolution of the universe. The first stellar generations are different from solar metallicity ($Z_\odot$) stars due to their low metal content or absence of it. First, very low-Z stars are more compact due to lower opacity. Second, *metal free* stars burn hydrogen in a core, which is denser and hotter. This implies that the transition between core hydrogen and helium burning is much shorter and smoother. Furthermore, hydrogen burns via the pp-chain in shell burning. *These differences make the metal free (first) stars different from the second or later generation stars!* (Ekström & Meynet 2007). Third, mass loss is metallicity dependent (at least for radiation-driven winds) and therefore mass loss is expected to become very small at very low metallicity. Finally, the initial mass function of the first stellar generations is expected to be top heavy below a certain threshold (Bromm & Loeb 2003).

Mass loss is expected to be very small. What could change this expectation? An additional mechanism or the chemical enrichment of the envelope of the star are two possible ways to increase mass loss at very low Z. Models of metal free stars including the effect of rotation (Ekström et al. 2005) show that stars may lose up to 10 % of their initial mass due to the star rotating at its critical limit (also called break-up limit). The mass loss due to the star reaching the critical limit is non-negligible but at the same time not important enough to change drastically the fate of the first generation stars.

The situation is very different at very low but non-zero metallicity (Meynet et al. 2006 and Hirschi 2007). The total mass of an 85 $M_\odot$ model at $Z = 10^{-8}$ is shown in Fig. 1 with the top solid line. This model, like metal free models, loses around 5% of its initial mass when its surface reaches break-up velocities in the second part of the main sequence. At the end of core H-burning, the core contracts and the envelope expands, thus decreasing the surface velocity and its ratio to the critical velocity. The mass loss rate becomes very low again until the star crosses the HR diagram and reaches the RSG stage. At this point the convective envelope dredges up CNO elements to the surface increasing its overall metallicity. The total metallicity, Z, is used in this model (including CNO elements) for the metallicity dependence of the mass loss.

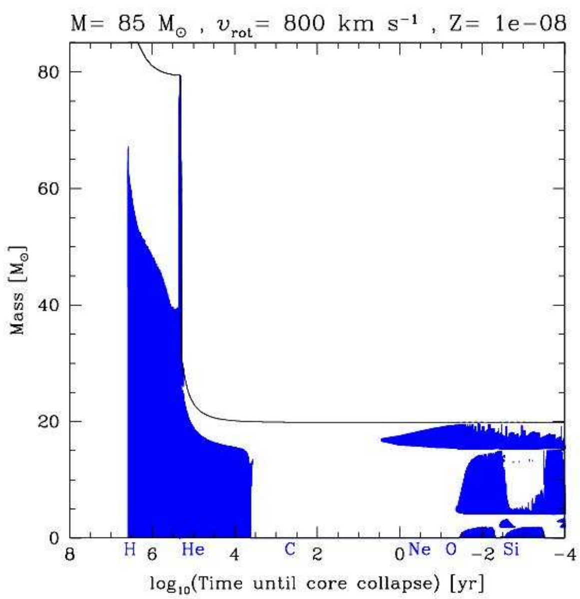

Figure 1: Structure evolution diagram of the 85 $M_\odot$ model at $Z = 10^{-8}$. Coloured areas corresponds to convective zones along the lagrangian mass coordinate as a function of time left until the core collapse. The top solid line shows the total mass of the star. The burning stage abbreviations are given below the time axis.

Therefore depending on how much CNO is brought up to the surface, the mass loss becomes very large again. The CNO brought to the surface comes from primary C and O produced in He-burning. Rotational and convective mixing brings these elements into the H-burning shell. A large fraction of the C and O is then transformed into primary nitrogen via the CNO cycle. Additional convective and rotational mixing is necessary to bring the primary CNO to the surface of the star. The whole process is complex and depends on mixing. Multi-dimensional models would be very helpful to constrain mixing between the hydrogen and carbon rich layers, which releases a large amount of energy and strongly affects the structure of the star.

The strongest mass loss occurs in these models in the cooler part of the HR diagram. Dust-driven winds appear to be metallicity independent as long as C-rich dust can form. For this to occur, the surface effective temperature needs to be low enough ($\log(T_{\rm eff}) < 3.6$) and carbon needs to be

more abundant than oxygen. Note that nucleation seeds (probably involving titanium) are still necessary to form C-rich dust. It is not clear whether extremely low-Z stars will reach such low effective temperatures. This depends on the opacity and the opacity tables used in these calculations did not account for the non-standard mixture of metals (high CNO and low iron abundance). It is interesting to note that the wind of the 85 $M_\odot$ model is richer in carbon than oxygen, thus allowing C-rich dust to form if nucleation seeds are present. There may also be other important types of wind, like chromospheric activity-driven, pulsation-driven, thermally-driven or continuum-driven winds.

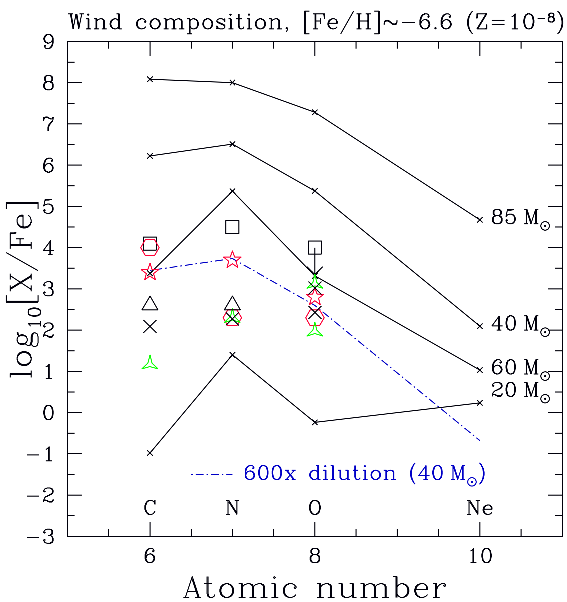

Figure 2: Composition in [X/Fe] of the stellar wind for the $Z = 10^{-8}$ models (solid lines). For HE1327-2326 (*red stars*), the best fit for the CNO elements is obtained by diluting the composition of the wind of the 40 $M_\odot$ model by a factor 600 (see Hirschi 2007 for more details).

Significant mass loss in very low-Z massive stars offers an interesting explanation for the strong enrichment in CNO elements of the most metal poor stars observed in the halo of the galaxy (see Meynet et al. 2006 and Hirschi 2007). The most metal poor stars known to date, HE1327-2326 (Frebel et al. 2006) is characterised by very high N, C and O abundances, high Na, Mg and Al abundances, a weak s–process enrichment and depleted lithium. The star is not evolved so has not had time to bring self–produced CNO elements to its surface and is most likely a subgiant. By using one or a few SNe and using a very large mass cut, Limongi et al. (2003) and Iwamoto et al. (2005) are able to reproduce the abundance of most elements. However they are not able to reproduce the nitrogen surface abundance of HE1327-2326 without rotational mixing. A lot of the features of this star are similar to the properties of the stellar winds of very metal poor rotating stars. HE1327-2326 could therefore have formed from gas, which was mainly enriched by stellar winds of rotating very low metallicity stars. In this scenario, a first generation of stars (PopIII) pollutes the interstellar medium to very low metallicities ([Fe/H]∼-6). Then a PopII.5 star (Hirschi 2005) like the 40 $M_\odot$ model calculated here pollutes (mainly through its wind) the interstellar medium out of which HE1327-2326 forms. This would mean that HE1327-2326 is a third generation star. In this scenario, the CNO abundances are well reproduced, in particular that of nitrogen, which according to the new values for a subgiant from Frebel et al. (2006) is 0.9 dex higher in [X/Fe] than oxygen. This is shown in Fig. 2 where the abundances of HE1327-2326 are represented by the red stars and the best fit is obtained by diluting the composition of the wind of the 40 $M_\odot$ model by a factor 600. When the SN contribution is added, the [X/Fe] ratio is usually lower for nitrogen than for oxygen. Although the existence of a lower limit for the minimum metallicity Z for low mass stars to form is still under debate, it is interesting to note that the very high CNO yields of the 40 $M_\odot$ stars brings the total metallicity Z above the limit for low mass star formation obtained in Bromm & Loeb (2003).

5 Gamma-ray bursts and pair-creation supernovae

Long and soft gamma-ray bursts (GRBs) have now been firmly connected to the death of type Ic supernovae (see Woosley & Bloom 2006 for a recent review). In one of the most promising models, the collapsar model (Woosley 1993), GRB progenitors must form a black hole, lose their hydrogen rich envelope (become a WR) and retain enough angular momentum in their core during the pre-supernova stages. The strong mass loss discussed in the previous section make it possible for single massive stars in the first stellar generations to become WR stars and even to retain enough angular momentum to produce a GRB (Hirschi 2007). A wider grid of models at metallicities around solar shows that the rate of fast rotating WO stars is compatible with the rate of GRBs with an upper limit around the LMC metallicity, in agreement with observations (Hirschi et al. 2005). More recent models including the effects of magnetic fields (Yoon & Langer 2005) show that another mechanism is possible to produce GRBs at low Z. This mechanism is the quasi-chemical evo-

lution of very fast rotating massive stars. In this scenario, WR stars are produced by mixing and not mass loss. This last scenario however does not predict GRB at metallicities equal or higher than the SMC. This upper limit is too low compared to recent observations (Fruchter et al. 2006). Taking into account the anisotropy in the wind of these fast rotating stars (Meynet & Maeder 2007) may help reduce the discrepancy between models and observations. Note that the downward revision of solar metallicity (Asplund et al. 2005) may also help resolve the problem.

Apart from GRBs, pair-creation supernovae (PCSNe) are very energetic explosions, which could be observed up to very high redshifts (Scannapieco et al. 2005). PCSNe are expected to follow the death of stars in the mass range between 100 and 250 $M_{\odot}$, assuming that they do not lose a significant fraction of their mass during the pre-supernova stages. Amongst the very first stars formed in the Universe, one expects to have PCSN due to the lack of mass loss and to the low opacity unable to stop the accretion on the star during its formation. However, the EMP stars observed in the halo of the galaxy do not show the peculiar chemical signature of PCSN (strong odd-even effect, see Heger & Woosley 2002). This means that either too few or even no PCSN existed. One possible explanation to avoid the production of very low-Z or metal free PCSNe is the strong mass loss in the cool part of the HR diagram due to the surface enrichment in CNO elements induced by rotational and convective mixing (see previous section) or the star reaching the $\Omega\Gamma$-limit (Ekström & Meynet 2007).

Acknowledgments. I wish to thank G. Meynet and S. Ekström for their help during the preparation of this review.

References

Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336: Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, 25
Beers, T. C. & Christlieb, N. 2005, ARA&A, 43, 531
Bouret, J.-C., Lanz, T., & Hillier, D. J. 2005, A&A, 438, 301
Bromm, V. & Loeb, A. 2003, Nature, 425, 812
Ekström, S. & Meynet, G. 2007, ArXiv e-prints:0708.1970, First Stars III conference proceedings
Ekström, S., Meynet, G., & Maeder, A. 2006, in ASP Conf. Series, Vol. 353, Stellar Evolution at Low Metallicity: Mass Loss, Explosions, Cosmology, ed. H. J. G. L. M. Lamers, N. Langer, T. Nugis, & K. Annuk, 141
Eldridge, J. J. & Vink, J. S. 2006, A&A, 452, 295
Ferrarotti, A. S. & Gail, H.-P. 2006, A&A, 447, 553
Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003a, MNRAS, 338, 360
Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003b, MNRAS, 338, 1025
Frebel, A., Christlieb, N., Norris, J. E., Aoki, W., & Asplund, M. 2006, ApJ, 638, L17
Fruchter, A. S., Levan, A. J., Strolger, L., et al. 2006, Nature, 441, 463
Fullerton, A. W., Massa, D. L., & Prinja, R. K. 2006, ApJ, 637, 1025
Heger, A. & Woosley, S. E. 2002, ApJ, 567, 532
Hirschi, R., Meynet, G., & Maeder, A. 2005, A&A, 443, 581
Hirschi, R. 2005, in IAU Symposium 228, ed. V. Hill, P. François, & F. Primas, 331–332
Hirschi, R. 2007, A&A, 461, 571
Höfner, S. & Andersen, A. C. 2007, A&A, 465, L39
Iwamoto, N., Umeda, H., Tominaga, N., Nomoto, K., & Maeda, K. 2005, Science, 309, 451
Kobulnicky, H. A., Fryer, C. L., & Kiminki, D. C. 2006, astro-ph/0605069, ApJ accepted
Kudritzki, R. P. 2002, ApJ, 577, 389
Kudritzki, R.-P. & Puls, J. 2000, ARA&A, 38, 613
Limongi, M., Chieffi, A., & Bonifacio, P. 2003, ApJ, 594, L123
Maeder, A. 1987, A&A, 178, 159
Maeder, A. & Desjacques, V. 2001, A&A, 372, L9
Meynet, G., Ekström, S., & Maeder, A. 2006, A&A, 447, 623
Meynet, G. & Maeder, A. 2007, A&A, 464, L11
Meynet, G. & Maeder, A. 2005, A&A, 429, 581
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Mokiem, M. R., de Koter, A., Vink, J. S., et al. 2007, ArXiv e-prints, 708
Nieuwenhuijzen, H. & de Jager, C. 1990, A&A, 231, 134
Porter, J. M. & Rivinius, T. 2003, PASP, 115, 1153
Scannapieco, E., Madau, P., Woosley, S., Heger, A., & Ferrara, A. 2005, ApJ, 633, 1031
Smith, N. & Owocki, S. P. 2006, ApJ, 645, L45
van Loon, J. T. 2006, in ASP Conf. Ser. 353: Stellar Evolution at Low Metallicity: Mass Loss, Explosions, Cosmology, ed. H. J. G. L. M. Lamers, N. Langer, T. Nugis, & K. Annuk, 211
van Loon, J. Th., Cioni, M.-R. L., Zijlstra, A. A. & Loup, C., A&A, 438, 273
van Loon, J. T. 2000, A&A, 354,125
Vanbeveren, D., Van Bever, J., & Belkus, H. 2007, ApJ, 662, L107
Vink, J. S. & de Koter, A. 2005, A&A, 442, 587
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2000, A&A, 362, 295
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574
Woosley, S. E. 1993, ApJ, 405, 273
Woosley, S. E. & Bloom, J. S. 2006, ARA&A, 44, 507
Yoon, S.-C. & Langer, N. 2005, A&A, 443, 643